The effects of forest type on soil microbial activity in Changbai Mountain, Northeast China

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ORIGINAL PAPER

The effects of forest type on soil microbial activity in Changbai Mountain, Northeast China

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Abstract

• ***Key message*** **Forty years after clear-cutting mixed old-growth forest (broadleaf/Korean pine) in the Changbai Mountain area (Northeast China), a mixed forest with natural broadleaf regeneration and larch plantation displayed larger microbial biomass and activity in the soil than either a naturally regenerated birch forest or a mono-specific spruce plantation.**

• ***Context*** Clear-cutting with limited restoration effort was until the end of the twentieth century the norm for managing primary forests in Northeast China. Forest restoration plays an important role in the recovery of soil quality after clear-cutting, but the effects of different regeneration procedures on forest soil quality remain poorly known in Northeast China.

• ***Aims*** We assessed the effects of three regeneration procedures, i.e., (i) naturally regenerated birch forest, (ii) spruce plantation, and (iii) naturally regenerated broadleaf species interspersed with planted larch on soil quality and microbial activity in the Changbai Mountain area. An old-growth mixed broadleaf/Korean pine forest was used as a reference.

• ***Methods*** Physical and chemical properties and microbial biomass were recorded in the soil. Basal respiration and carbon mineralization were measured with a closed-jar alkali-absorption method.

• ***Results*** Microbial biomass was smaller in the birch forest and spruce plantation than in the old-growth and the mixed broadleaf/larch forests. Moreover, microbial biomass, microbial quotient, and potentially mineralizable carbon were larger in the mixed broadleaf/larch than in the birch forest, while no difference was found between spruce plantation and birch forest for microbial biomass and microbial quotient. Basal respiration and metabolic quotient were larger in the birch forest as compared to the three other forest types, indicating a larger energy need for maintenance of the microbial community and lower microbial activity in the naturally regenerated birch forest.

• ***Conclusion*** Mixed broadleaf/larch forest displayed a larger microbial biomass and higher substrate use efficiency of the soil microbial community than either naturally regenerated birch forest or spruce plantation. The combined natural and artificial regeneration procedure (mixed broadleaf-larch forest) seems better suited to restore soil quality after clear-cutting in the Changbai Mountain.

Keywords Forest restoration · Soil quality · Microbial biomass carbon · Carbon mineralization · Changbai Mountain

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Contribution of the co-authors Fang X. and Yu D. designed the experiments, statistically analyzed on data, and wrote the manuscript; Fang X., Zhou W. and Zhou L. set up sample plots and did field works; Fang X. and Zhou L. contributed to laboratory tests; Dai L. Funding support.

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1 Introduction

Forest soil is closely associated not only with the carbon cycle (Fahey et al. 2013), but also with the nutrient pool that determines vegetation productivity (Aertsen et al. 2012). In Northeast China, clear-cutting was a common forest management practice for many decades until the turn of the century (Yu et al. 2011). Clear-cutting of primary forests often leads to changes in vegetation types and structure, which together with the subsequent variety of litter inputs and forest microclimates (Staddon et al. 1997) may lead to irreversible impacts on forest soil quality (Guo et al. 2010; Yan et al. 2013; Wang et al. 2015). Clear-cutting induced soil degeneration can be reflected in acceleration of soil organic matter mineralization, modifications in the amount and quality of organic residues and their redistribution, changes in soil structure, and increases in erosive processes (Wu et al. 2011; Fang et al. 2014). Artificial regeneration can effectively prevent soil erosion and soil degradation after clear-cutting (Yu et al. 2011; Bini et al. 2013). In Northeast China, due to various reasons including economics (lack of financial support) and topography (e.g., steep terrain), artificial regeneration was not conducted in most clear-cut areas, which were simply left to develop naturally after harvesting (Dai et al. 2003; Nowak 2012). However, few relevant studies were undertaken with respect to the influence of different restoration methods on forest soil.

Physical and chemical properties have been used to evaluate the quality of soils, such as organic matter, nutrient status, runoff measurements, and aggregate formation (Poeplau et al. 2011; Six and Paustian 2014). However, these properties change slowly, and thus, it requires a long time to detect significant changes. In contrast, some soil microbial properties sensitive to disturbance, such as microbial biomass and enzyme activities, are used as bioindicators for monitoring the quality and health in soils (Bini et al. 2013; Raiesi and Beheshti 2015). Previous studies have shown that soil microbial biomass, respiration rates, and metabolic quotients are sensitive indicators of changes produced by forest type conversion (Gamboa and Galicia 2011; Bini et al. 2013; Spohn and Chodak 2015). Likewise, carbon (C) mineralization, which is related to nutrient release for plants and soil organisms, may reveal potential microbial activity in the soil and is sensitive to land use and management (Zhang et al. 2009; Cheng et al. 2014; Fang et al. 2014).

Forest conversion can significantly impact soil conditions and microbial activity, which are likely to respond to harvesting, soil organic matter removal, and tree species change (Gamboa and Galicia 2011; Lin et al. 2011; Fang et al. 2014). Due to logging disturbance and reduction of substrate availability, the amount of microorganisms and microbial activity will generally decrease with conversion of primary to secondary forests (Gamboa and Galicia 2011; Bini et al. 2013). For instance, Bini et al. (2013) found that primary forests had more microbial biomass C than secondary forests or plantations and that metabolic quotients as well as dehydrogenase activity increased after primary forest conversion. In clear-cut areas, a restoration method of artificial conifer-broadleaf mixed forest has been recommended, since soil C, nitrogen, and microbial activity have been found to be lower in monoculture plantations compared to mixed forests (Xu et al. 2007). Anderson and Domsch (1993) reported that metabolic quotient values decreased in a mixed forest ecosystem compared with those measured for single plantation forest ecosystems. However, some studies have argued that artificial regeneration with coniferous species maintains a larger soil carbon pool, being more sustainable in the temperate zone of Northeast China (Yu et al. 2011). In this light, which regeneration method is more effective remains an open question.

In the Changbai Mountain area, as primary forest, mixed broad-leaved/Korean pine (*Pinus koraiensis* Sieb. et Zucc.) forest was widely distributed as recently as several decades ago (Yu et al. 2011). Unfortunately, about 20 % of the primary forest area was harvested by clear-cutting in the period of 1950 to 1985. Larch (*Larix olgensis* Henry) and spruce (*Picea asperata* Mast.) plantations were often reforested and managed with near natural growth measures after clear-cutting in this area (Liu et al. 2005; Shi et al. 2008; Yu et al. 2011). Larch plantations subsequently developed into broadleaf-conifer mixed forests with larch as the dominant species, reflecting a lower survival rate for larch, while spruce formed pure coniferous plantations decades later. Birch (*Betula platyphylla* Suk.) forests, naturally restored through secondary succession, were also common in this region (Dai et al. 2003; Liu et al. 2005). However, we know relatively little about the impacts of different regeneration pathways on soil microbial biomass and its activity, which are related to soil quality and forest sustainability.

In this study, we measured and compared soil physicochemical properties, soil microbial biomass, respiration, and C mineralization characteristics (representing microbial activity) in old-growth forest, birch forest, mixed broadleaf/larch forest, and spruce plantation. The following two major questions were addressed: (1) Are the microbial biomass and microbial activity higher in old-growth forest than in the restored forest types? (2) Is microbial activity greater in mixed broadleaf/larch forest compared to birch forest and spruce plantation, each of which reflects a different mode of forest restoration? Our results may provide a basis for more effective forest management regimes in Northeast China and elsewhere.

2 Materials and methods

2.1 Study site

This study was conducted in one of the representative temperate forest zones in the Changbai Mountain area of Northeast China administered by the Lushuihe Forest Bureau, in Fusong county of Jilin province (127° 29′–128° 02′ E, 42° 20′–42° 40′ N). The climate of the region is temperate continental with significant seasonal variation in both temperature and precipitation. Atmospheric temperature ranges from −6 to 40.7 °C, and mean annual temperature is about 0.9 to 1.5 °C. Mean annual precipitation is 800–1040 mm with most occurring between July and August. The soil of the experimental fields is brown forest soil, classified as Udalfs according to the second edition of U.S. Soil Taxonomy, with a thickness of 60–80 cm. Mean altitude ranges from 600 to 800 m above sea level.

The Lushuihe Forest Bureau was founded in the late 1960s, and logging was not conducted until 1968 (Yu et al. 2004). Prior to that time forests administered by the Bureau were almost all primary old-growth mixed broadleaf/Korean pine forest, dominated by Korean pine and native broadleaf tree species including *Tilia amurensis* Rupr., *Quercus mongolica* Fisch. ex Ledeb., and *Fraxinus mandschurica* Rupr. In the 1970s, the primary forest began to be harvested via clear-cutting and reforested via the planting of 3-year-old seedlings of larch and spruce. Larch plantations experienced no human disturbance and formed a mixed forest with larch as the dominant species after 40 years (about 50 % of total stand basal area), along with natural broadleaf species (Bao et al. 2014), including *Phellodendron amurense* Rupr., *Juglans mandshurica* Maxim., *Acer pseudo-sieboldianum* (Pax) Komarov, and *T. amurensis*. Spruce plantations formed a pure conifer forest after 40 years with a less diverse herbaceous understory. Natural recovery through secondary succession after old-growth forest clear-cutting was also a common management approach adopted by the Bureau. In these cases, the pioneer species of natural regeneration after clear-cutting was birch (*B. platyphylla)*, and after 40 years growth regenerated birch forest was also comprised of some other broadleaf species (e.g., *P. amurense*, *F. mandshurica*, *T. amurensis*) as well as occasionally a minor component of conifers. In 1985, the Lushuihe Bureau began to implement selective cutting. Thus, naturally regenerated birch forest, spruce plantation and mixed forest with natural broadleaf regeneration, and larch plantation recovered from clear-cutting dominate the study area currently, and only 221 ha of primary (i.e., old-growth) forest remains under management of the Lushuihe Forest Bureau, which did, however, provide us an ideal reference in studying the soil quality in different forest types. Therefore, these four major forest types were selected.

2.2 Experiment design and soil sampling

This work was conducted based on Forestry Standards "Observation Methodology for Long-term Forest Ecosystem Research" of People's Republic of China (LY/T 1952–2011). For three forest types—birch forest, mixed broadleaf/larch forest, and spruce plantation—four compartments (forest management unit in China forestry, mostly 50–200 ha) for each at least 1000 m apart were selected as sample sites. For old-growth forest, since only one compartment remains (221 ha in total) in the Lushuihe Bureau, all the four sample sites were located in it. One plot (20 m × 20 m) was established in each sample site. Tree composition and stand structure were measured in September 2008 (Table 1). The soils were sampled in July 2011. Litter and humus horizon were removed before soil sampling. In each plot, 15 points were randomly selected using an S-shaped soil sampling pattern to decrease spatial heterogeneity and a stainless steel auger (5 cm in diameter) to collect samples from 0 to 10 cm depth. Soil samples were thoroughly mixed to form a composite for each plot. All samples were immediately placed in boxes with ice bags and transported to the laboratory for analysis. After roots and organic debris were removed by hand, field-moist soil samples were sieved with 2 mm mesh and divided into two parts. The first was stored at 4 °C for determination of soil microbial biomass, respiration, and C mineralization within 2 weeks, while the other part was air-dried to analyze soil organic C, total nitrogen (N), and pH.

2.3 Analyses of soil samples

Soil pH was measured in a 1:2.5 mixture of soil and deionized water using a glass electrode. Soil bulk density was determined using a 100 cm^3 metal cylinder, and soil moisture was calculated gravimetrically by drying soils at 105 °C overnight and subsequently expressing water content as a percentage of the dry weight. All soil samples were oven-dried and sieved with a 0.15-mm screen prior to measuring soil organic C via the dichromate oxidation method (Nelson and Sommers 1996) and total N using the Kjeldahl method (Allen 1989).

Microbial biomass C was determined by a fumigation-extraction procedure (Vance et al. 1987; Cai et al. 2011). In brief, two portions of moist soil (equivalent to 25 g oven-dried soil) were weighed. One was fumigated for 24 h at 25 °C with ethanol-free $CHCl_3$ and then was extracted with 50 mL of 0.5 M K_2SO_4 for 30 min by oscillated shaking at 180 r min^{-1} and filtering. For the other (not fumigated) portion was immediately extracted as described above. Organic C in the extracts was determined after oxidation with 0.2 M $K_2Cr_2O_7$ at 180 °C for 5 min (Lin et al. 1999). Specifically, the extracted solution (10 mL), concentrated sulfuric acid (5 mL), and potassium dichromate (5 mL, 0.2 M) were mixed and heated in a 180 °C oil bath for 5 min. The reaction mixture was titrated using 0.05 M ferrous sulfate to calculate the organic C content.

Microbial biomass was calculated as follows:

$$MBC = EC/K_{EC}$$

where *EC* is the difference between organic C extracted from fumigated and non-fumigated soils, and K_{EC} = 0.38.

Basal respiration and C mineralization were determined via the method described by Zhang et al. (2009). In brief, C mineralization was measured using moist soil (equivalent to 25 g oven-dried soil), moistened to 60 % of its water holding capacity and placed in stoppered glass jars (150 mL) at 25 °C. The CO_2 emitted was collected in 10 mL 0.1 M NaOH after 1, 2, 3, 5, 7, 9, 14, 21, 28, 35, 42, 49, and 57 days of incubation, respectively, and titrated with 0.05 M HCl. Jars without soils were used as a background reference. Once the sampling of a

Table 1 Stand characteristics of four forest types in the Changbai Mountain region of Northeast China

Stand characteristics	Forest types[a]			
	Old-growth forest	Birch forest	Mixed broadleaf/larch forest	Spruce plantation
Canopy coverage (%)	90	80	80	85
Mean tree age (year)	>150	42	42	42
Stand density (stem ha^{-1})	928	2556	1496	1105
Mean diameter at breast height (cm)	15.8	8.66	8.68	7.52
Basal area (m^2 ha^{-1})	18.3	15.1	8.52	4.91
Vegetation biomass (t ha^{-1})	305	147	191	172
Litter layer biomass (t ha^{-1})	37.2	20.6	116.0	136.4

[a] Old-growth forest is a primary mixed forest with broadleaf and Korean pine; birch forest is regenerated by natural succession; mixed broadleaf/larch forest is a mixed forest with natural broadleaf regeneration and larch plantation

jar was completed, it was flushed with ambient air and resealed for the next measurement. Basal respiration was determined by CO_2 production after 1 day (Hofman et al. 2003).

Data were fitted to a conventional first-order kinetics equation [$C_m = C_0(1 - e^{-kt})$] to measure C mineralization kinetics (Riffaldi et al. 1996; Moscatelli et al. 2007), in which C_m is the cumulative value of mineralized carbon during t days; C_0 is the potentially mineralizable carbon; and k is the rate constant of carbon mineralization. $t_{0.5}$ is calculated by ln2/k. Additional derived parameters were also calculated (Moscatelli et al. 2007). These indices included C_m/C_0—the ratio of C mineralized to potentially mineralizable C over 57 days and C_0/SOC—the ratio of potentially mineralizable C to soil organic C. Microbial quotient was calculated as microbial biomass C/soil organic C; and metabolic quotient (qCO_2), representing the microbial respiration per biomass unit, was calculated as basal respiration/microbial biomass C (Anderson and Domsch 1990).

2.4 Data and statistical analysis

Statistical analysis was performed using the SPSS 13.0 software package for Windows. Data were analyzed via one-way analysis of variance (ANOVA), and least significant difference (LSD) ($p < 0.05$) was used to compare means when treatment effects were significant. Pearson's correlation was utilized to determine whether there were significant correlations among measured properties of the soils. C mineralization kinetics was fitted via a nonlinear curve method utilizing Origin 8.5 software.

3 Results

3.1 Soil physical and chemical characteristics

Soil pH and bulk density were slightly greater in the forest plots of naturally regenerated birch forest, spruce plantation, and mixed broadleaf/larch forest than in old-growth mixed broadleaf//Korean pine forest (Table 2). However, no significant differences among these three forest types were found. Soil moisture was higher in old-growth forest as compared to the three other forest types. Meanwhile, soil moisture in mixed broadleaf/larch forest was significantly higher than that in birch forest and spruce plantation. The concentration of soil organic C was significantly higher in old-growth forest than that in birch forest, mixed broadleaf/larch forest, and spruce plantation, by 26, 33, and 37 %, respectively. Similarly, total N concentration in birch forest, mixed broadleaf/larch forest, and spruce plantation was lower than that in old-growth forest by 31, 27, and 35 %, respectively. No significant differences in soil organic C and total N concentration were found among birch forest, mixed broadleaf/larch forest, and spruce plantation. The soil C/N ratio of birch forest was 11.8, significantly higher than that of mixed broadleaf/larch forest.

3.2 Microbial biomass carbon, basal respiration and microbial indices

Microbial biomass C in spruce plantation was significantly lower by 41 % compared to that in old-growth forest, and a significant difference was also found between spruce plantation and mixed broadleaf/larch forest (Table 3). Soil basal respiration in birch forest did not differ significantly from that in old-growth forest, although soil basal respiration in birch forest was significantly higher than that in mixed broadleaf/larch forest and spruce plantation. Soil qCO_2 was significantly higher in the birch forest than in the other three types, while microbial quotient was significantly higher in the mixed broadleaf/larch forest than in the other three forest types (Table 3).

3.3 Soil carbon mineralization characteristics and indices

The potentially mineralizable carbon (C_0) was lower in birch forest than the other three forest types. With respect to C_m, the

Table 2 Soil physical-chemical characteristics of four forest types in the Changbai Mountain region of, Northeast China

Forest types[a]	pH (H_2O)	Bulk density ($g\ cm^{-3}$)	Moisture (%)	Organic C ($g\ kg^{-1}$)	Total N ($g\ kg^{-1}$)	C/N
Old-growth forest	4.79 ± 0.26a	0.52 ± 0.04a	80.3 ± 2.8a	88.6 ± 9.1a	8.10 ± 0.72a	10.9 ± 0.1ab
Birch forest	4.87 ± 0.34a	0.57 ± 0.14a	46.2 ± 5.9c	65.4 ± 7.1b	5.57 ± 0.66b	11.8 ± 0.2a
Mixed broadleaf/larch forest	4.81 ± 0.20a	0.55 ± 0.14a	62.8 ± 6.7b	59.1 ± 5.1b	5.91 ± 0.48b	10.0 ± 0.6b
Spruce plantation	5.13 ± 0.30a	0.58 ± 0.12a	46.8 ± 6.3c	55.9 ± 4.2b	5.23 ± 0.94b	10.7 ± 0.7ab

Data are means ± standard deviation ($n = 4$). Different letters indicate significant differences among the four forest types at $p < 0.05$

Organic C organic carbon, *Total N* total nitrogen

[a] Old-growth forest is a primary mixed forest with broadleaf and Korean pine; birch forest is regenerated by natural succession; mixed broadleaf/larch forest is a mixed forest with natural broadleaf regeneration and larch plantation

highest value occurred in old-growth forest soil and the lowest value in spruce plantation soil (Fig. 1). The C_m/C_0 ratio displayed a significantly higher value for the birch forest relative to that for spruce plantation and mixed broadleaf/larch forest soils (Fig. 2a). The average soil respiration rate was higher in birch forest than in mixed broadleaf/larch forest and spruce plantation soils, and no significant differences were detected here (Fig. 2b). $t_{0.5}$ ranged from 39.4 days for birch forest to 80.2 days for spruce plantation, and a significant difference was detected between birch forest and spruce plantation. Meanwhile, C_0/soil organic C was significantly higher in spruce plantation and mixed broadleaf/larch forest soils than in birch forest and old-growth forest soils (Table 4).

3.4 Correlations between microbiological activities and chemical parameters

C_m displayed a positive correlation with microbial biomass C and basal respiration, while C_0 was not correlated with any microbiological index (Table 5). Microbial quotient showed a positive correlation with microbial biomass C and was negatively correlated with qCO_2. And qCO_2 was positively correlated with basal respiration.

In order to better understand the causes of variations in the different microbial activities, the relationships between soil microbial parameters and soil physicochemical properties were also analyzed. The results showed that microbial biomass C was significantly and positively related to soil organic C, total N, and moisture (Table 6). Basal respiration was positively linked with soil organic C and soil C/N ratio. qCO_2 was positively and significantly correlated with soil C/N ratio. Likewise, C_m was positively and significantly related to soil organic C and total N, while C_0 had no significant correlation with any soil chemical property.

4 Discussion

Maintaining and improving soil quality is one of the important objectives of forest management. Our previous study showed that reforestation was more conducive to the preservation of soil organic matter than any type of farmland after clear-cutting in this area (Yu et al. 2011; Fang et al. 2014). As for the restored forest, soil quality was influenced by many factors, such as stand age, organic inputs, and microbial communities (Jia et al. 2005). This study selected three forest types with the same age, same origination, and no human

Table 3 Soil microbial properties of four forest types in the Changbai Mountain region of Northeast China

Forest types[a]	Microbial biomass C ($mg\ kg^{-1}$)	Basal respiration ($mg\ CO_2–C\ kg^{-1}\ day^{-1}$)	qCO_2 ($mg\ CO_2–C\ mg\ MBC^{-1}\ day^{-1}$)	Microbial quotient (%)
Old-growth forest	1377 ± 208a	139.0 ± 23.8ab	0.10 ± 0.02b	1.54 ± 0.16b
Birch forest	942 ± 118b	155.0 ± 28.7a	0.17 ± 0.04a	1.43 ± 0.12b
Mixed broadleaf/larch forest	1310 ± 154a	97.4 ± 15.3b	0.07 ± 0.04b	2.21 ± 0.08a
Spruce plantation	818 ± 121b	93.4 ± 22.2b	0.11 ± 0.02b	1.42 ± 0.18b

Data are means ± standard deviation ($n = 4$). Different letters indicate significant differences among the four forest types at $p < 0.05$

qCO_2 metabolic quotient

[a] Old-growth forest is a primary mixed forest with broadleaf and Korean pine; birch forest is regenerated by natural succession; mixed broadleaf/larch forest is a mixed forest with natural broadleaf regeneration and larch plantation

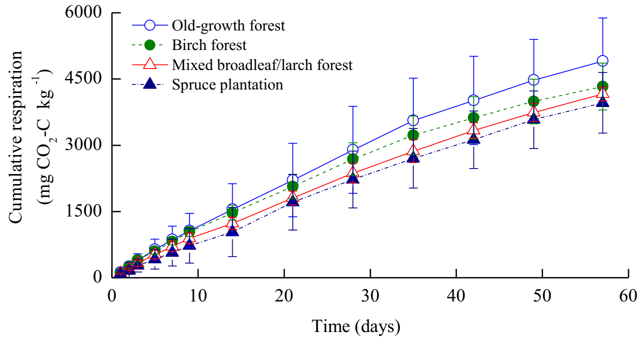

Fig. 1 Cumulative mineralization of soil carbon over 57 days incubation for four forest types in the Changbai Mountain region of Northeast China. *Vertical bars* show standard deviations ($n=4$). Old-growth forest is a primary mixed forest with broadleaf and Korean pine; birch forest is regenerated by natural succession; mixed broadleaf/larch forest is a mixed forest with natural broadleaf regeneration and larch plantation

disturbance in the process of forest restoration, trying to reflect the effects of forest types on soil quality. Generally, most soil systems are resource-limited, and microbial biomass is therefore usually strongly related to soil organic matter and nitrogen concentration (Wardle 1992; Shi et al. 2008). Higher and steady inputs of carbon through litter-fall production, fine root production, and exudations as well as mycorrhizal associations are likely to be the driving factors resulting in relatively higher soil microbial biomass (Joergensen et al. 1995). Soil with low organic carbon usually has lower microbial biomass and vice versa (Islam et al. 2000; Fang et al. 2014). In this study, old-growth mixed broadleaf/Korean pine forest and mixed broadleaf/larch forest had a larger microbial biomass C than birch forest and spruce plantations (Table 3), which was attributable to the higher organic matter and nitrogen concentration under the mixed forests than under birch and spruce forests (Table 2). This result was consistent with those reported by Jia et al. (2005), who found that soil microbial biomass was strongly correlated with soil organic C and total N concentrations at different stages of secondary forests. Meanwhile, litter diversity was also a factor linked to microbial biomass C, since soil microbial biomass and the activity of associated enzymes increased in areas with high litter diversity, and a mixture of leaf litter could improve the quality of forest soil (Hu et al. 2006). For instance, Thoms et al. (2010) reported that the highest levels of leaf litter diversity had the largest total amounts of fatty acids and that arbuscular mycorrhizal fungi was significantly increased with leaf litter diversity in temperate deciduous forest. In this light, the higher microbial biomass C in old-growth forest and mixed broadleaf/larch forest relative to that in birch forest and spruce plantation may be induced by a higher species diversity in mixed forests. Additionally, although there was no difference of soil organic C and total N among three reforested forest types, the higher soil moisture in mixed broadleaf/larch forest relative to that in birch forest and spruce plantation may be the main reason leading to higher microbial biomass C in mixed broadleaf/larch forest compared to that in birch forest and spruce plantation (Table 2), given that soil microbial biomass often declined upon soil drying and increased upon re-wetting (Baldrian et al. 2010; Brockett et al. 2012), and soil under wet conditions had higher amount of microbial biomass than that in dry soil (Islam et al. 2000).

Soil basal respiration can reflect the overall activity of microorganisms (Anderson and Domsch 1990). Xu et al. (2007)

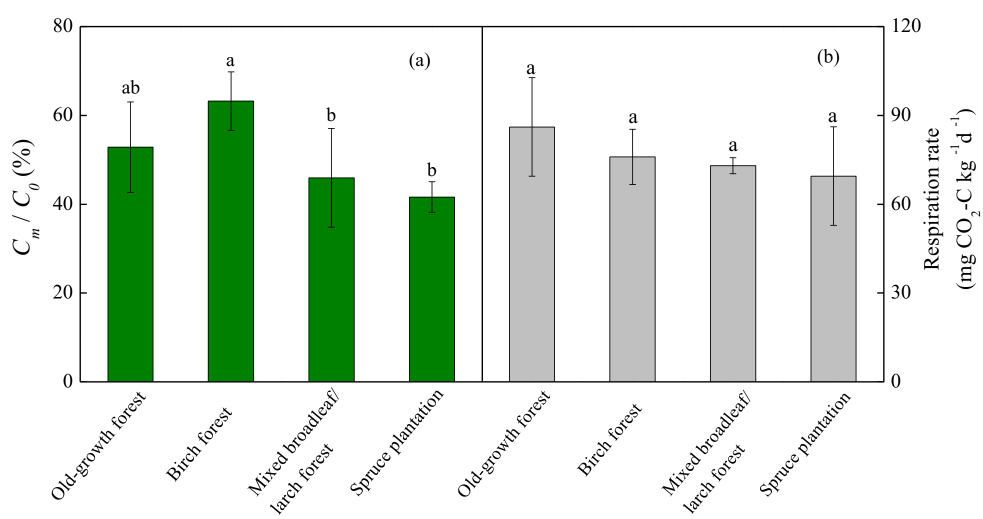

Fig. 2 Ratio of soil cumulative mineralized carbon to potentially mineralizable carbon (C_m/C_0) (**a**) and mean respiration rate (**b**) after 57 days incubation for four forest types in the Changbai Mountain region of Northeast China. Carbon mineralization modeling is based on $C_m = C_0\ (1\text{-}e^{-kt})$, where C_m and C_0 are cumulative amount of carbon mineralization within the incubation period and potential mineralized carbon, respectively; k is the mineralization constant and t is time period (days). *Vertical bars* show the standard deviation of the mean ($n=4$). Old-growth forest is a primary mixed forest with broadleaf and Korean pine; birch forest is regenerated by natural succession; mixed broadleaf/larch forest is a mixed forest with natural broadleaf regeneration and larch plantation

Table 4 Kinetic parameters for soil carbon mineralization of four forest types in the Changbai Mountain region of Northeast China

Forest types[a]	C_0 (mg CO_2–C kg^{-1})	k (day^{-1})	$t_{0.5}$ (day)	R^2	C_0/soil organic C (%)
Old-growth forest	9296 ± 926a	0.014 ± 0.004ab	53.8 ± 18.2ab	0.999 ± 0.001a	2.87 ± 0.58b
Birch forest	6896 ± 747b	0.018 ± 0.004a	39.4 ± 6.8b	0.999 ± 0.001a	2.88 ± 0.44b
Mixed broadleaf/larch forest	9532 ± 915a	0.011 ± 0.004b	69.0 ± 23.0ab	0.999 ± 0.001a	4.48 ± 0.66a
Spruce plantation	9380 ± 1188a	0.009 ± 0.004b	80.2 ± 25.4a	0.996 ± 0.003a	4.56 ± 0.80a

Data are means ± standard deviation ($n = 4$). Different letters indicate the significant differences in the four forest types at $p < 0.05$. Calculated with the formula $C_m = C_0\ (1\text{-}e^{-kt})$

C_0 potentially mineralizable carbon, C_m cumulative value of mineralized carbon during 57 days, k rate constant of carbon mineralization, $t_{0.5}$ days required for attaining half potential percentage of carbon mineralized

[a] Old-growth forest is a primary mixed forest with broadleaf and Korean pine; birch forest is regenerated by natural succession; mixed broadleaf/larch forest is a mixed forest with natural broadleaf regeneration and larch plantation

found that a natural broadleaf-Korean pine forest at an age above 150 years in the Changbai Mountain area had entered an advanced successional stage, which often induced higher microbial activity. However, the significant differences of mean respiration rate were not found among the four forest types (Fig. 2b). Generally, a high rate of respiration indicates high microbial activity, while some studies have argued that it is difficult to detect the true modification of microbial activity only via the use of basal respiration measurement (Navarro-García et al. 2012), since some CO_2–C released in soil respiration is used to provide energy for microbial maintenance. However, the index of metabolic quotient (qCO_2, ratio of basal respiration/microbial biomass C) can be used to represent actual microbial activity (Insam and Domsch 1988; Anderson and Domsch 1990) and to evaluate the substrate utilization efficiency of soil microbial communities (Anderson and Domsch 1993). A greater energy need for maintenance can be detected at the microbial community level by a higher CO_2–C evolution rate per cell mass and unit time, which results in a higher qCO_2 (Anderson and Domsch 1993; Xu et al. 2007). The higher value of qCO_2 in birch forest found may illustrate that there was less microbial activity and lower substrate utilization efficiency of the soil microbial community in the birch forest when compared to old-growth forest, mixed broadleaf/larch forest, and spruce plantation. This result may be supported by the fact that the total CO_2 efflux from secondary birch forests in the same study region was about 1.3 times greater than that in old-growth forest during the growing season (May–September) (Wang et al. 2007).

In this study, we found a positive correlation between qCO_2 and C/N. qCO_2 increased with C/N ratios may be caused by that soil microorganisms respired more C both in absolute terms and per unit of microbial biomass C when decomposing substrate with lower N concentration (Kanerva and Smolander 2007; Spohn 2014; Spohn and Chodak 2015). Birch forest and spruce plantation soils had a relatively lower total N and higher C/N compared with mixed forests (old-growth forest and mixed broadleaf/larch forest). Therefore, higher soil C/N was possibly associated with the higher value of qCO_2 in birch forest, which led to soil microorganisms diverting more energy from growth into maintenance.

C_0 is a practical tool for evaluating the substrate availability for heterotrophic populations in soil, which can represent the size of the soil active organic carbon pool (Moscatelli et al. 2007). The value of C_0 was significantly lower in birch forest compared with other forest types, which may indicate that birch forest has depleted more soil biodegradable C pools through faster biodegradation rates relative to old-growth forest, mixed broadleaf/larch forest, and spruce plantation (e.g., basal respiration and qCO_2) (Table 3), suggesting that mixed broadleaf/

Table 5 Correlation matrix for soil microbial activity indices in four forest types in the Changbai Mountain region of Northeast China ($n = 16$)

	Microbial biomass C	Basal respiration	qCO_2	Microbial quotient	C_m
Microbial biomass C	1.00				
Basal respiration	0.40	1.00			
qCO_2	−0.48	0.60*	1.00		
Microbial quotient	0.64*	−0.17	−0.65*	1.00	
C_m	0.74**	0.71*	−0.01	0.22	1.00
C_0	0.40	−0.05	−0.44	0.36	0.53

qCO_2 metabolic quotient, C_m cumulative value of mineralized carbon over 57 days, C_0 potentially mineralizable carbon

* $p < 0.05$; ** $p < 0.01$

Table 6 Pearson's correlations between soil microbial activity indices and physical-chemical properties of soils in four forest types in the Changbai Mountain region of Northeast China ($n = 16$)

	Microbial biomass C	Basal respiration	qCO_2	Microbial quotient	C_m	C_0
pH	−0.22	−0.50	−0.27	−0.03	−0.36	−0.15
Bulk density	−0.02	−0.01	−0.06	−0.12	−0.06	−0.07
Moisture	0.75**	0.28	−0.39	0.22	0.44	0.23
Organic C	0.76**	0.68*	−0.06	−0.01	0.79**	0.24
Total N	0.85***	0.52	−0.29	0.17	0.74**	0.33
C/N	−0.21	0.66*	0.81***	−0.57	0.28	−0.27

qCO_2 metabolic quotient, C_m cumulative value of mineralized carbon over 57 days, C_0 potentially mineralizable carbon

$^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$

larch forest and spruce plantation had a higher availability of soil organic matter than in birch forest. Likewise, the parameter C_0/soil organic C ratios can provide additional information on the differences in carbon availability, which responds readily to disturbance effects and can provide an effective warning on the deterioration of soil quality (Moscatelli et al. 2007; Fang et al. 2014). The value of C_0/SOC was greater in mixed broadleaf/larch forest and spruce plantation than in birch forest, indicating that there were more degradable substrates in the soil of these forests than that in birch forest soil and that the ability of supplying nutrients is more enhanced under mixed broadleaf/larch forest and spruce plantation soils. Similarly, the higher C_m/C_0 ratio in the birch secondary forest may be ascribed to the enhancement of biodegradation rates as a result of forest conversion, since the ratio of C_m to C_0 can reflect either the size or the quality of the mineralizable C pool in different land uses (Moscatelli et al. 2007).

On an overall basis, our results revealed that mixed broadleaf/larch forest had a higher microbial biomass and activity compared to birch forest and spruce plantation. Based on the results from our current and previous study (Fang et al. 2014), we recommend that cultivating larch with native broad-leaved species may be a feasible method to meet the soil and environmental conservation demands associated with reforesting clear-cut areas in the Changbai Mountain region. It is true, of course, that tree species composition and stand structure will change with forest age, which in turn will affect the amount and quality of litter input to the forest floor, ultimately affecting soil quality (e.g., Jia et al. 2005). This study focused exclusively on the soil condition at a certain stage of forest succession (40 years). Variations in soil quality over the longer time spans of forest life cycles merit continued attention and research efforts.

5 Conclusion

Our results clearly showed that forest conversion from old-growth forest to naturally regenerated birch forest, mixed natural broadleaf/larch plantation forest, and spruce plantation significantly reduced soil nutrients (soil organic C and total N) and microbial biomass. The greatest decrease in microbial activity occurred in the conversion of old-growth forest to secondary birch forest. In comparison with birch forest, the higher value of microbial biomass C, basal respiration, and the lower qCO_2 in mixed broadleaf/larch forest indicated that this type of restored forest had a higher amount of soil microorganisms and substrate utilization efficiency of the soil microbial community, which reflects a better soil quality. This result suggests that the combined natural and artificial approach of restoring mixed broadleaf/larch forest may be a better way to restore soil quality after forest clear-cutting in the temperate forest area of Northeast China.

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